

Evidence of a distinct stellar population in the counter-rotating core of NGC 1700

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ABSTRACT

We find a distinct stellar population in the counter-rotating and kinematically decoupled core of the isolated massive elliptical galaxy NGC 1700. Coinciding with the edge of this core we find a significant change in the slope of the gradient of various representative absorption line indices. Our age estimate for this core is markedly younger than the main body of the galaxy. We find lower values for the age, metallicity and Mg/Fe abundance ratio in the center of this galaxy when we compare them with other isolated elliptical galaxies with similar velocity dispersion. We discuss the different possible scenarios that might have lead to the formation of this younger kinematically decoupled structure and conclude that, in light of our findings, the ingestion of a small stellar companion on a retrograde orbit is the most favoured.

Subject headings: galaxies: elliptical and lenticular, cD— galaxies: interactions —galaxies: kinematics and dynamics —galaxies: stellar content

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1. Introduction

Galaxies with kinematically decoupled cores (KDC, hereafter) are very interesting systems to test ideas of galaxy formation. The SAURON survey found that ~ 30 per cent of early-type galaxies have KDCs (de Zeeuw et al. 2002; McDermid et al. 2006). Their distinct angular momenta suggest that the cores may be relics of interactions or mergers and thus may provide a diagnostic to estimate the relevance of these processes in shaping galactic properties (e.g., Kormendy 1984; Franx & Illingworth 1988; Schweizer et al. 1990; Bender & Surma 1992).

The origin of the KDC is still a mystery (Illingworth & Franx 1989; Bender 1990), but the coupling between kinematic and stellar population studies can provide the necessary clues for achieving a more complete picture. Several possible scenarios have been proposed (see Bender 1990 and references therein): (1) geometrical projection of the stellar orbits in the core of an ordinary triaxial potential (Statler 1991). Obviously, breaks in the stellar population properties of the KDC and the rest of the galaxy are not expected in this case; (2) a central stellar disc formed from accreted gas with an initial counter-rotating orbit (Franx & Illingworth 1988; Bertola et al. 1998). Under this process, however, it would not be possible to form some of the observed massive KDC. For example, the mass of the KDC of NGC 5322 is $\sim 10^{10} M_{\odot}$ (Bender & Surma 1992), which is significantly higher than the gaseous mass that an irregular gaseous galaxy would contribute with; (3) a central disc formed during a major merger of two spirals (Schweizer et al. 1990; Hernquist & Barnes 1991). The gas and stars react very differently to the merger process and the angular momentum of both components can be very different, leading to this kind of structures, and (4) the remnant of an accreted stellar companion, initially orbiting contrary to the mean rotation of the galaxy (Kormendy 1984; Balcells & Quinn 1990). The companion would be partially destroyed but its nucleus would become part of the decoupled core of the host galaxy. In this scenario we expect to find breaks between the stellar populations of the KDC and the rest of the galaxy. Low-mass galaxies have, in general, younger populations and lower metallicities than their massive counterparts (e.g., Sánchez-Blázquez et al. 2006b), so we would expect to find a drop in these two parameters;

So far, a clear difference in the stellar populations of KDC and the host galaxy has not been found, at least in galaxies with central velocity dispersion above 100 km s^{-1} (eg., Carollo et al. 1997; Mehlert et al. 1998; Davies et al. 2001; Sánchez-Blázquez 2004; Kuntschner et al. 2010). Several authors have reported that KDCs show enhanced metallicity using colours (eg., Bender & Surma 1992; Carollo & Danzinger 1994b). However, Sánchez-Blázquez (2004) shows that these variations were more likely due to the presence of dust discs by comparing the measurements in colours and line-strength indices. She found that the variations were

only visible in the colours and molecular indices, more affected by dust, but not in the atomic indices, insensitive to its presence (MacArthur 2005).

An exception to this, ie, differences in the stellar populations properties of KDC and the host galaxy, happens when the KDC is small (~ 0.1 - 0.3 kpc) and it is in the center of low-massive early-type galaxies (with central velocity dispersion σ around 100 km s^{-1}). In these cases the nucleus appear to be younger and more metal rich than the rest of the galaxy (McDermid et al. 2006). These young nuclei are found, exclusively, in fast rotating galaxies (see Emsellem et al. 2004 for the definition) and are much less massive than the 'classical' KDC. The formation of these nuclei are probably related to the accretion of a gaseous small galaxy (second of the scenarios listed above).

Here we present the kinematics and the stellar population of NGC 1700 to show that it represents an interesting and unique case of KDC. The layout is as follows: Sec 2 describes the relevant properties of this galaxy; Sec 3 describes the observations, data reduction and kinematic measurements; Sec 4 describes the stellar population study. Finally, in Sec 5 we present a discussion and our conclusions.

2. Relevant galaxy properties

NGC 1700 is an elliptical galaxy with a weakly counterrotating core (Franx et al. 1989b; Saha & Williams 1994; Bender et al. 1994; Statler et al. 1999). The galaxy is fairly bright, with $M_B = -22.3$, and massive, with $\sigma = 230 \text{ km s}^{-1}$ (Bender et al. 1992). Its rather high surface brightness and uncharacteristically small effective radius ($r_{\text{eff}} \sim 14''$ ($2.6 \text{ h}^{-1}/\text{kpc}$) (Franx et al. 1989a), put it slightly less than 2σ off the FP in the sense of having unusually low M/L for galaxies of this mass. The galaxy is boxy inside 3 arcsec and discy outside this radius (Carollo et al. 1997). The ellipticity continuously rises outward and shows structure clearly identified with the variations in the fourth order cosine term. The discy isophotes and the peak in ellipticity indicate the presence of a stellar disc between 3 and 10 arcsec. NGC 1700 shows several characteristics of being the result of a merger that happened ~ 5.5 - 8.3 Gyr ago (Schweizer & Seitzer 1992). However, Statler et al. (1996) claimed that the radially increasing prograde rotation in the main body of the galaxy implies that the major merger event was not responsible for the counterrotating core. They suggest that the KDC in NGC 1700 is more likely the result of a merger of 3 or more stellar systems 2 - 4 h^{-1} Gyr ago, based on N-body simulations (Weil 1995). The surface brightness profile of this galaxy is well fitted with a Sersic law with $n = 5.5$ (Trujillo et al 2004) and does not show any "break" or slope change at the position of the KDC (Brown et al. 2000).

3. Observations, Kinematics and absorption line-strengths

Long-slit spectroscopy was acquired for this galaxy with the blue channel of the ISIS spectrograph on the 4.2m William Herschel Telescope on 20-22 Nov 2000 within a sample of 9 elliptical galaxies covering a range of masses and in isolated environments (see Bergmann 2002). This configuration gives a wavelength coverage from 3650 to 5650 Å at resolution 2.63 Å(FWHM). Four exposures of ~ 35 m, with the slit positioned along the major axis, were taken for this galaxy in two nights. These observations were interspersed with flat-field and arc-lamp spectra. A selection of F,G, and K stars from the MILES library (Sánchez-Blázquez et al. 2006a; Cenarro et al. 2007) were also observed to be used as kinematical templates and for calibration purposes. Standard data reduction procedures (flat-fielding, cosmic-ray removal, wavelength calibration, sky subtraction and fluxing) were performed with `reduceme`, which allows a parallel treatment of data and error frames and provided an associated error file for each individual data spectrum.

Kinematical measurements were performed with the penalized pixel fitting method (`ppxf`, Cappellari & Emsellem 2004). The first two moments, line-of-sight velocity (LOSv) and velocity dispersion (LOSvD) were derived and also the higher order Gauss-Hermite moments, h_3 and h_4 , which measure deviations of the LOSvD from a pure Gaussian. Figure 1 shows the results for NGC 1700.

Line-strength indices with the Lick definition (Trager et al. 1998) and the metallicity-insensitive index $H\beta_o$ (Cervantes & Vazdekis 2009) were measured in our spectra previously degraded to a total width¹ of 14 Å (FWHM) to match the LIS-14 Å system proposed in Vazdekis et al. (2010). This avoids us to make any correction for the velocity dispersion of the galaxy, which can introduce systematic trends in the relation of the line-strength indices with other quantities. Figure 2 shows the variation of some selected indices with radius for NGC 1700. A linear fit, weighting with the index errors and discarding the seeing-affected central 1.3 arcsec region, is shown inside and outside the radius of the KDC.

4. Stellar populations

Figure 3 shows some index-index diagrams comparing different metallicity-sensitive indices with the optimized age-sensitive index $H\beta_o$. Over-plotted are the predictions of Vazdekis et al. (2010) single-stellar-population (SSP) models for different ages and metallic-

¹total width = $\sqrt{(FWHM_{\text{inst}}^2 + FWHM_{\text{gal}}^2)}$, where $FWHM_{\text{inst}}$ is the instrumental resolution and $FWHM_{\text{gal}}$ the Doppler widening due to the random motion of the stars.

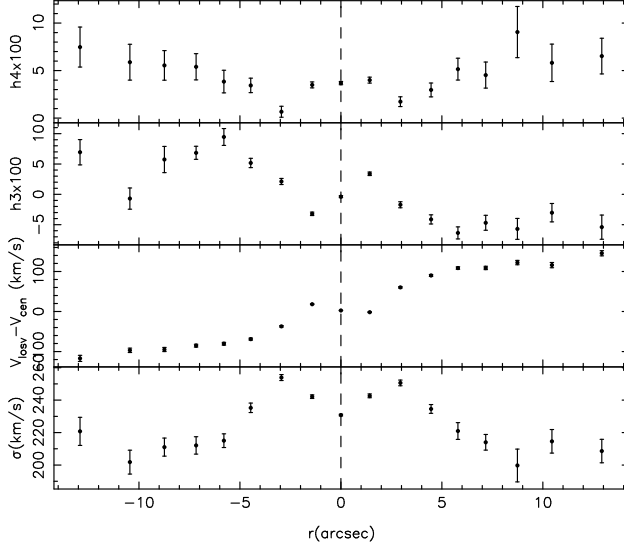


Fig. 1.— High order Gauss-Hermite moments, radial velocity and velocity dispersion versus the radius of NGC 1700.

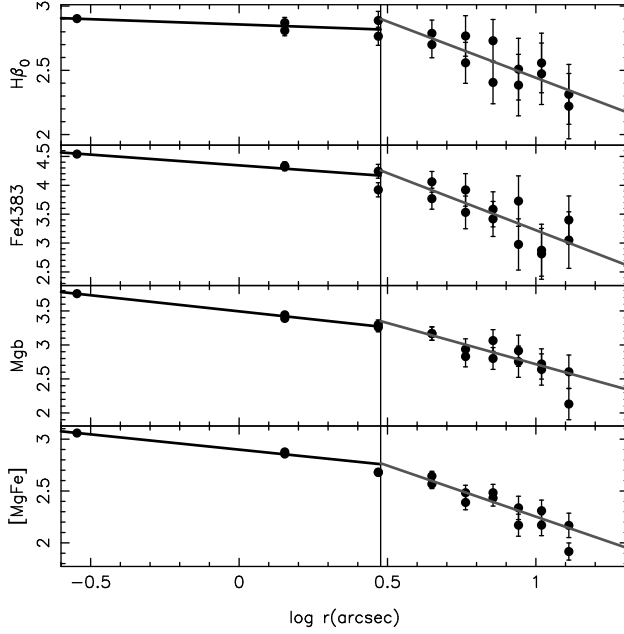


Fig. 2.— Line-strength indices along the radius for the galaxy NGC 1700. Black and grey lines show a linear-fit for the regions inside and outside the KDC respectively. The binning have into account the seeing of the observations ($\text{FWHM} \sim 1.3''$).

ities. Note that $H\beta_o$ provides a virtually orthogonal model grid. Over-plotted are the linear fits inside and outside the KDC that are shown in Fig. 2.

We have derived ages and metallicities by linearly interpolating the models to the values of the indices in the $[MgFe]'$ vs. $H\beta_o$ diagram. The $[MgFe]'$ index is insensitive to deviations from $[Mg/Fe]=0$, which occurs in giant ellipticals and which bias the ages, depending on the metallicity indicator in use (Thomas, Maraston & Bender 2003). To measure these deviations, we also have obtained metallicities using other indicators which are more sensitive to variations of Fe (Fe4383) and Mg (Mgb). The ages inferred from the different panels are similar, but there are differences in the metallicity that can be used to estimate the abundance ratios; if a galaxy spectrum is enhanced in Mg/Fe, we obtain a higher metallicity when Mgb is used instead of Fe4383. The metallicity difference obtained in this way, $[Z_{Mg}/Z_{Fe}]$, is a good proxy for the abundance ratio $[Mg/Fe]$. In fact, a linear relation between the ratio Z_{Mg}/Z_{Fe} and the $[Mg/Fe]$ values derived directly from the Thomas et al. (2003) models – which specifically take into account non-solar abundance ratios – was found in Vazdekis et al. (2010) (see also Sánchez-Blázquez et al. 2006b; de la Rosa et al. 2007).

Figure. 4 shows the variation of the mean² age, metallicity and $[Z_{Mg}/Z_{Fe}]$ with radius for NGC 1700. Unlike the rest of the galaxy, the KDC region shows a clearly younger and nearly constant SSP-equivalent age of ~ 6 Gyr. The KDC also shows a metallicity and $[Z_{Mg}/Z_{Fe}]$ gradient that is flatter than in the main body of the galaxy.

Due to the presence of gradients in elliptical galaxies, and to the fact that these do not correlate clearly with any other general property, if we want to know the stellar populations of the core in relation to the main body of the galaxy, we need to compare the central stellar population parameters of NGC 1700 with those of other galaxies when plotted against σ central. It is well known that the stellar populations in the elliptical family are very correlated with this parameter. For this purpose we have extracted the central spectra inside an aperture of $r_e/10$, where r_e represents the effective radius of the galaxy, for the complete sample of this observing run, consisting of isolated ellipticals covering a range in mass. This radius, in the case of NGC 1700 corresponds approximately to half of the radius of the KDC. We correct for the effect of rotation before extracting the central spectra. We also correct for the presence of emission lines in two galaxies NGC 1172 and NGC 661 using **gandalf** (Sarzi et al. 2006). We have measured the indices and σ and calculated the metallicities with different indicators as above. Figure 5 shows the age, metallicity and Z_{Mg}/Z_{Fe} in the central $r_{eff}/10$ for our sample of galaxies as a function of the central σ . It can be seen that

²Note that these values are SSP-equivalent values, and they would be biased towards the most luminous stellar populations

NGC 1700 is younger and have a lower $[Z/H]$ and $[Z_{Mg}/Z_{Fe}]$ than what it would be expected, giving its σ , from the relation defined by the rest of the sample.

5. Discussion

We have shown that the KDC in NGC 1700 have a distinct stellar population than the rest of the galaxy. This is probably the first time that such feature has been found in a ‘classical’ KDC. Although claimed by previous authors (see the introduction), this was, in most cases, due to the presence of a dusty disc, affecting colours and molecular indices, or an artifact of plotting the profiles in linear instead of in logarithmic scale, while the line-strength profiles follow a power-law. McDermid et al. (2006) already found younger components in the KDCs of some early-type galaxies, however there are important differences as (1) the size of the young nuclei in the McDermid et al. (2006) sample is never larger than 0.3 kpc, while the KDC in NGC 1700 is ~ 0.8 kpc and (2) all the galaxies with younger nuclei in McDermid et al. (2006) have $\sigma \sim 100 \text{ km s}^{-1}$, while NGC 1700 is massive, with $\sigma \sim 230 \text{ km s}^{-1}$.

As described in the introduction, four scenarios have been proposed to explain the formation of these structures: (1) geometrical projection of stellar orbits in the core of a triaxial system; (2) a central disc formed from accreted gas with an initial counter-rotating orbit;³ (3) a central disc formed during the merger of two spirals and (4) accretion of a stellar companion initially counter-rotating with respect to the galaxy. In addition to these four scenarios, we also considered the possibility that the KDC was the end-of-view of a bar that within a hot disc (this galaxy has a stellar disc from 3 to 10 arcsec). Such system would explain the counter-rotating feature in the center and the decrease in σ observed in that region due to the ordered motion of the bar (e.g., Bureau & Athanassoula 2005; de Lorenzo-Cáceres 2008). However we do not see any hint of counter-rotation in the stellar disc of this galaxy, as it would be expected if the bar form from it. Only in the case that the disc contribution to the total light in the region we are sampling is negligible, this possibility cannot be fully discarded.

Scenario 1 does not seem to apply to NGC 1700 as the stellar populations should not differ in the transition to the KDC. Such change is, however, possible for scenarios 2, 3 and 4.

³Hau & Thomson (1994) also proposed that the spinning up of the halo of a previously non-rotating elliptical that contains a small, high surface brightness disc by a flyby encounter could produce kinematically decoupled structures. The elliptical is left with a central inner disc rotating in a different direction than the halo.

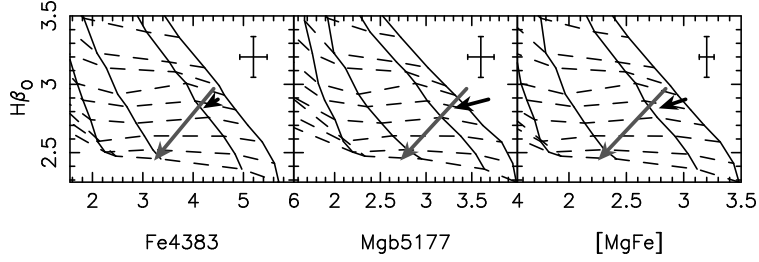


Fig. 3.— Index-index diagrams comparing the age-sensitive $H\beta_o$ index (Cervantes & Vazdekis 2009) with different metallicity-sensitive indices in the LIS-14Å system (Vazdekis et al. 2010). Over-plotted are the predictions of Vazdekis et al. (2010) models of constant age (dashed lines) and metallicity (solid lines). The values of the different represented ages are (from top to bottom: 1.8, 2.2, 2.8, 3.5, 4.5, 5.6, 7.1, 8.9, 11.2, 14.1, 17.8 Gyr, while the values of metallicities are (from left to right: $[Z/H]=-0.4$, 0.0, $+0.22$). The linear fits from Fig. 2 are represented in the Figure. The region inside the KDC is plotted in black while we represent, in grey, the region outside the KDC. The arrow indicates the direction toward larger radius in each case. Typical errors on each index are plotted as error bars on the right upper corner of each panel.

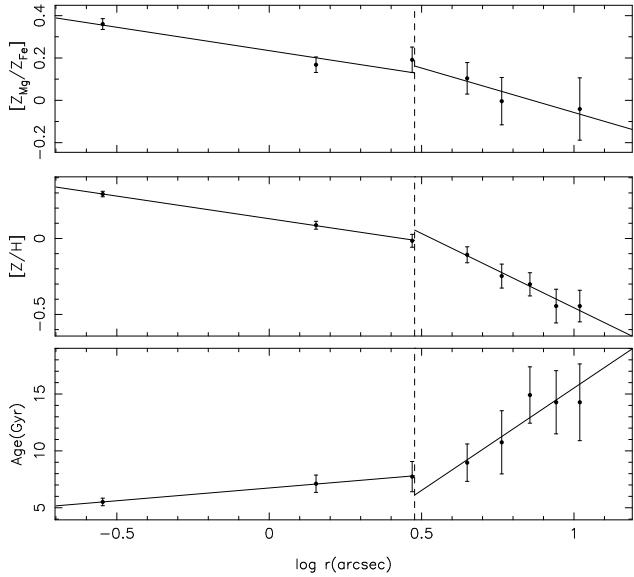


Fig. 4.— Stellar population parameters of NGC 1700 as a function of radius. The area corresponding to the KDC is indicated with a vertical dashed line. To guide the eye, linear fits inside and outside the KDC are also plotted.

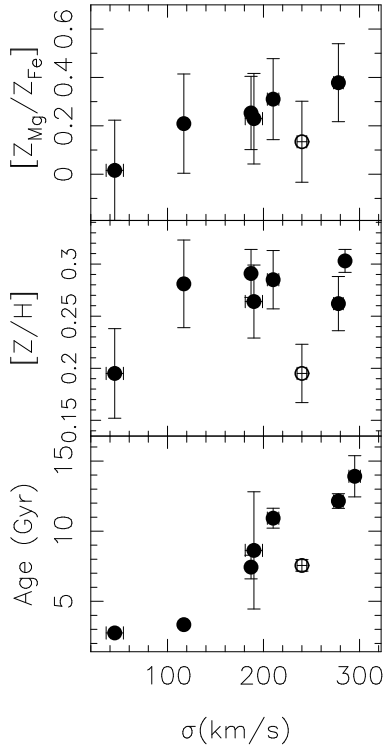


Fig. 5.— Age, metallicity (measured with a $[\text{MgFe}]\text{-H}\beta_o$ diagram), and the abundance ratio proxy $Z_{\text{Mg}}/Z_{\text{Fe}}$ measured in the central spectra ($r_e/10$) of a sample of field ellipticals of varying mass is plotted vs. σ . The open symbol represents NGC 1700.

Scenario 2, as we already mentioned, is most likely to form the small KDCs found in McDermid et al. (2006), as the involved mass would be compatible with that contributed by an irregular gaseous galaxy⁴.

Regarding the third scenario, NGC 1700 shows several signatures of having experienced a merger with a gaseous system (such as tidal tails, see eg., Brown et al. 2000). Ages of this merger have been estimated using fine structure ages (Schweizer & Seitzer 1992; 6.0 ± 2.3 Gyr and dynamical ages (Statler 1996; $2.7 = 5.3$ Gyr). These ages are consistent with our age estimate for the KDC of this galaxy. The central value of the abundance ratio, lower than expected for its σ , is also compatible with our estimate, as we would expect $[\text{Mg}/\text{Fe}]$ to be lower if the gas comes from processed gas in spiral galaxies (Thomas 1999).

However, kinematical arguments, as the low rotation and low skewness h_3 would not be expected if the central component was produced in a gaseous merger (e.g., Bak 2000; Naab et al. 2006), ie., are not expected if the central kinematical component was a disc as in the case of, for example, IC 1459. Furthermore, Statler et al. (1996) already pointed out that the radially increasing prograde motion with radius at $R > 50$ arcsec argues against a single merger event in this galaxy. A single merger would not deposit prograde orbiting stars at large radius and retrograde at small radius. NGC 1700 must have merged with or ingested at least two other stellar systems to account for its present dynamical structure.

Scenario 4 has been modelled by Balcells & Quinn (1990). Balcells (1991) obtained coefficients of skewness ~ 0.2 corresponding to $h_3 \sim 0.03$, very near to the values we measure in the core of NGC 1700 ~ 0.05 . Furthermore, Balcells & Quinn (1990) confirm Kormendy’s (1984) conjecture that the central velocity dispersion of the remnant should be slightly depressed, as the light here is contributed significantly by the core of a less massive system. We also observe a depression of σ in the central region of NGC 1700 (note that this feature is not observed in IC 1459 where the kinematically decoupled structure is more likely produced by a disc). In the scenario proposed by Balcells & Quinn (1990) we would expect to find lower age, metallicity and $[\text{Mg}/\text{Fe}]$ as expected for a low mass early-type galaxy. All this holds for the center of NGC 1700.

We conclude that the most likely scenario for NGC 1700 is the ingestion of a small stellar companion on a retrograde orbit as the cause of counterrotating core, with a later gaseous merger, responsible for the tidal tails observed in this galaxy.

⁴Using stellar population models we estimate a stellar mass for the KDC of $8.9 \times 10^{10} M_{\odot}$

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